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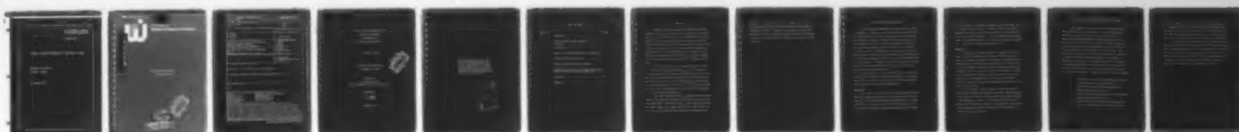

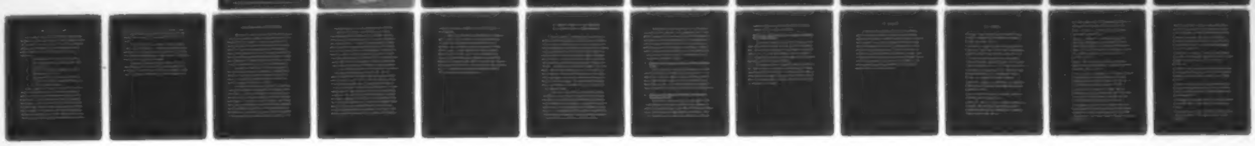

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T.H. TOPPER
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Cumulative damage procedures based on a local stress-strain approach which includes an adequate description of metal processing, plastic deformation history and resulting residual stresses, can adequately predict fatigue for uniaxial stress at temperatures where metal deformation is time dependent. The extension of these procedures to biaxial stressing and elevated temperatures is possible for limited cases but much remains to be done before general applicability is possible. Models for reversed plastic deformation capable of describing structural plasticity have been successfully applied to several metals and geometries. Load history characterization by generalized models is on the other hand applicable only in a few restricted cases.

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T. H. TOPPER
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I. INTRODUCTION

Cumulative damage procedures based on reversal by reversal computations of the stress-strain history at potential crack initiation sites have successfully been used to analyse complicated load histories. Many of the features of fatigue under these conditions including the creation and relaxation of residual stresses and the resolution of events in complicated stress-strain strain histories are now incorporated in these procedures. The treatment of others such as changes in metal ductility and hardness due to metal working and in surface topography due to plastic straining at high load levels are incorporated in this report.

However existing models of the fatigue process are limited by the lack of reliable plasticity solutions for cyclic loading of structural components and of suitable characterizations of service load histories. Also the quantitative descriptions of the fatigue process are generally accurate only for time independent uniaxial deformation. Service conditions however may give rise to biaxial stressing at fatigue critical locations and temperatures high enough that metal deformation can not be considered time independent.

This report describes advances in generalizing metal deformation models to describing the repeated plastic deformation of structures and structural elements. Characterizations of service loadings which retain the elements essential for damage analysis yet are simple enough to be dealt with computationally have been developed for restricted cases.

An example of a successful biaxial fatigue analysis is given and experimental equipment and test techniques devised to provide data for extending the analysis to complex plastic deformations is described. Experimental evidence also shows that time independent and creep damage interactions must be included in site prediction procedures for elevated temperatures.

II. FATIGUE CUMULATIVE DAMAGE PROCEDURES

Cumulative damage procedures suitable for predicting the crack initiation phase of fatigue life have been developed in previous phases of this program and have now been integrated with a general structural load deformation to produce a comprehensive prediction procedure. The latter element is dealt with in the following section of this report and the general procedure is reviewed in reference [1]. Essentially this method is based on determining the local stress-strain history at potential crack initiation sites, and correlating the damaging events taken as closed loops with similar events in reference tests on sample specimens. In this correlation it is important to retain the effect of stress-strain history in producing residual stresses which govern the mean stress associated with each stress-strain loop.

Other features of the prior strain history of a metal element which have been identified as having a pronounced effect on subsequent crack initiation are plastic straining due to overloads and heavy cold working such as that caused by stamping operations.

Overstrains

The plastic strains associated with occasional high load levels while small enough to have little effect on the hardness or ductility in many metals, a marked reduction in subsequent fatigue life. Topper and Watson [2] who summarized many of these effects showed that in a variety of cases the metals which showed a life reduction of following

plastic straining also evidenced metalographic notching when viewed under a scanning electronic microscope. On the other hand, the metals they examined which failed to show metalographic notching or surface damage, also failed to show life reduction. Other investigations have suggested, however, that other mechanisms such as a reduction in aging due to periodic plastic straining can also produce life reductions [3].

Cold Working

The degree of cold work required for stamping operations often marked by increased metal hardness and sharply reduces the ductility. A series of experiments designed to measure changes in fatigue resistance associated with these high levels of cold work are reported in reference [4]. While as expected, the short life fatigue resistance decreased as increasing cold work reduced metal ductility, the accompanying increases in the long life fatigue resistance. Indeed the suppression of plastic straining due to increased hardness following very severe stamping, resulted in increases in fatigue resistance measured as the basis of strain level of up to 50 percent.

Taken together, these investigations suggest that straight forward damage accumulation procedures based on local stresses and strains at crack initiation sites can be used to predict fatigue crack initiation. In their application, however, it is mandatory that changes in metal structure due to deformations experienced during fabrication and, surface notching and residual stresses induced by plastic straining during service loading be accounted for.

III. INELASTIC LOAD DEFORMATION RESPONSE OF STRUCTURES

A continuation of previous work [5,6] which showed that the nominal load versus local strain history of a notched member exhibits characteristics similar to the stress versus strain behavior of a smooth specimen has been generalized and experimentally verified for structural elements and structures. Reference [7] and [8] demonstrates this similarity of load-local strain behavior to material stress-strain behavior for several types of specimens and several materials. The regularity of the nominal load-local strain behavior and the availability of mathematical modelling techniques instigated an investigation in fatigue life prediction using a computerized version of the mathematical rules and experimental data for the nominal load-local strain transform for the particular geometry, and local strain-local stress and fatigue life curves for the material. Computer simulation runs have been completed on:

1. RQC-100 Steel "keyhole" edge notched specimens subjected to the SAE load histories proposed in Ref. 9.
2. Boron Steel centre notched specimens subjected to a pseudo-random load history. (Ref. 10).
3. 7075-T6 Aluminum box beams subjected to variable amplitude block loading using data from Ref. 11.
4. 2024-T3 Aluminum centre notched specimens subjected to one of the SAE standardized load histories (Ref. 12).

The fatigue life prediction results were generally within a factor of three of the test lives, except for the box beam simulations where factors as large as five were observed. It is believed that the lack of mean stress relaxation capabilities in the "steady state" model used were a contributing factor in this discrepancy in life predictions.

Boron steel notched plate experimental data has indicated that differences exist between a nominal load-local strain transform computed from a incremental step test, and the transform derived from equal fatigue life data for notched and smooth specimens. A similar discrepancy is apparent in the transform of the RQC-100 notched steel specimens reported in reference 10. Several notched plate experiments are planned to determine the reasons behind the transformation differences.

IV. FATIGUE SERVICE HISTORY ANALYSIS

In the areas of structural testing and fatigue damage evaluation the measurement of service loads, or strains, has been an important component of design procedure. Due to the relative lack of rules for service history measurement and use in subsequent testing, an investigation has been initiated to determine criteria which may guide engineers to solve problems such as:

1. What characteristics of the load (or strain) service history must be measured e.g. peaks and valleys, ranges, level crossings, etc.
2. How large a data sample is required to ensure that no important features are missed.
3. What simplifications, such as truncation or omission of cycles are allowable for subsequent component testing or cumulative damage computations.

Several concurrent projects aimed at clarifying these criteria are in progress. Algorithms have been written for operation on digital computers for the collection of several types of statistics on service history variables. Of these a single pass "rainflow" type of counter appears promising. It retains or allows for the history effects during random loading-effect which are missed by counting methods such as level crossings for example. The combination of the rainflow algorithm with a microprocessor also shows promise as a fatigue counter for use on vehicles. Other work in the literature also indicates the feasibility of such fatigue

counters. No actual construction of such a unit is presently planned in this research program but the algorithm is being used in full scale computers to collect statistics on the service histories used in the research.

Another algorithm has been implemented for filtering small half-cycles out of a load history. An attempt will be made to establish criteria for reliable simplification and shortening of service histories used for specimen or prototype testing. Experiments with different degrees and types of half-cycle omission are underway.

References [13] and [14] illustrate progress to date on the problem of developing a stochastic model for determining damage due to load histories. To date the models used explain the fundamental features observed in deterministic models but are restricted to simple histories.

V. BIAXIAL STRESS-STRAIN AND FATIGUE BEHAVIOR

Reference [15] points out that the biaxial stresses often present at crack initiation sites,may substantially change the fatigue life from that found for uniaxial stressing. The analysis presented in this reference further shows that when the biaxial nature of these stresses is taken into account and an appropriate failure criterion employed changes in fatigue resistance and in the notch strength reduction factor based on the assumption of uniaxial stressing may be explained. Revised notch strength reductions computed using the biaxial stresses and failure criterion then allow accurate crack initiation fatigue predictions.

Often however, calculation of the stress-strain history on which these calculations are based is hampered by an inadequate understanding of metal plastic deformation response under cyclic biaxial stressing. An experimental investigation aimed at clarifying this behavior is now partially completed [16,17,18,19].

It developed a biaxial fatigue criterion for the tubular mild steel specimens subjected to tension-compression loading and internal-external pressure. However, the experimental work was conducted on a testing system that was limited to producing stress ratios fixed by the specimen geometry. In addition, the amount of bending in the specimen wall was found to be relatively large and some difficulties encountered with the instrumentation used during the initial experimental study required attention. During the last year, a new biaxial system capable of producing any ratio of stresses has been tested and refined. A new

specimen design intended to give uniform deformation in the test section has also proven to be successful. This modification of the biaxial testing equipment permits independent control of the strain magnitudes occurring in the two principal directions of the cyclically deformed thin-walled tubular specimen. As a result, both proportional and non-proportional cyclic inelastic biaxial deformation excursions within or between any of the four principal stress or strain quadrants can be experimentally examined. Presently, the biaxial stress-strain response of a mild steel tested under various fixed ratios of principal strain is being investigated. A testing scheme that uses the new equipment to produce a greater amount of useful data to be obtained from each specimen is now being implemented.

Initial deformation response of the virgin metal is first recorded at the corresponding prescribed principal strain ratio. Next the specimen is subjected to an incremental proportional straining program to evaluate the transient effects of cyclic hardening or softening occurring at the given principal strain ratio. This straining program causes the mild steel to pass through an initial transitory phase after which a stable deformation pattern, unique to the particular strain ratio being imposed, is established. When stabilization of the material behavior is achieved, the specimen is subjected to a short history of variable principal strain limits to obtain the characteristics of stable cyclic deformation response exhibited by a mild steel subjected to biaxial inelastic straining. The degree of material instability re-introducing by the history is then assessed by subjecting the specimen to the incremental cyclic deformation

program until the transient component of cyclic material behavior has once again disappeared.

Stable biaxial deformation data obtained during the experimental program is used to check the validity of extending simplified models of uniaxial reversed plasticity to conditions of biaxial cyclic deformation. This investigation represents a continuation of previous studies [7,25,26]. In these studies, several different structural elements were shown to exhibit cyclic force - deformation behavior similar to the stress-strain response displayed by uniaxial specimens. Furthermore, a simplified procedure capable of modelling stable deformation response proved to be successful in both stress-strain and force-deformation space. It is hoped that this modelling procedure may be extended to conditions of stable cyclic biaxial deformation.

VI. INTERACTION OF FATIGUE AND CREEP DAMAGE DURING CYCLIC INEALSTIC STRAINING AT ELEVATED TEMPERATURES

Previously described, accomplishments toward the objective of producing a fatigue cumulative damage procedure capable of predicting the lives of structural components have been limited to situations in which the material deformation and fracture may be assumed to be time independent. During high temperature fatigue this cumulative damage procedure is not accurate because both time independent and time dependent deformations must be considered. In this case, two kinds of damage, fatigue damage (time independent), and creep damage (time dependent) accumulate at the same time. The interaction of these two types of damage is still largely unknown. Physically the fatigue damage is due to the localization of plastic deformation in the grains of the metal or the alloy in question and the creep damage is due to the part of the inelastic strain that is localized on the grain boundaries. Many research workers assume that fatigue and creep damages can be added linearly as a fracture criteria for high temperature fatigue.

In this work, fatigue and creep interaction process during high temperature of cyclic inelastic deformation of a metallurgically stable material, annealed OFHC copper and commercial purity copper at different temperatures are being examined. Cyclic deformation tests were conducted using a closed loop servocontrolled electrohydraulic testing system in air. Surface damage and fracture surfaces were examined using a scanning electron microscope while the related dislocation substructure was observed using thin film transmission electron microscopy.

The dependency of stress response and life on cyclic frequency was studied and it was found that at high frequencies the life is independent of temperature and the fatigue cracks initiates and propagates in an intercrystalline manner (fatigue damage) while at low frequencies the life was highly temperature dependent and the fatigue cracks initiated and propagated totally on the grain boundaries (creep damage). Frequencies required to produce pure fatigue damage and pure creep damage were specified on this basis and blocks consisting of specified damage fractions were imposed on the specimens as follows:-

[A] <u>Sequence of a fatigue fraction followed by a constant creep damage fraction</u>:-

This series of tests were applied to OFHC copper at two temperatures 540°C and 300°C and to commercial purity copper at 540°C. It was observed that a low value of damage to failure occurred when very small fatigue damage fraction was imposed in each block followed by a small damage fraction of creep. As the number of fatigue cycles increased, the fracture mode changed from mainly intercrystalline to mainly transcrystalline.

[B] <u>Sequence of a creep damage fraction followed by constant small fatigue damage fraction</u>:-

This series of tests were carried out on OFHC copper at 540°C, a controlled number of low frequency (creep) cycles was imposed on the specimen and this was followed by a small number of high frequency (fatigue) cycles. The resulting linear damage summation line indicated a strong interaction between creep and fatigue under conditions when a very small

creep damage was followed by very small fatigue damage in each block. All specimens in this series failed intergranually.

[C] <u>Sequential block testing with each block containing a fixed damage ratio of creep to fatigue</u>:-

In this series, varying controlled number of creep cycles were imposed followed by a given number of fatigue cycles to form a complete block. The ratio of the creep damage to fatigue damage in each block was constant at 2.0. The linear damage summation line shows a minimum at small creep damage fractions and as the creep damage increases the linearly summed damage for failure increases continually.

All the present results on damage interaction indicates that the total damage to failure is a function of the characteristics of damage distribution imposed on the material. At certain distributions there is a minimum where the total damage to failure is far less than unity and the level of this minimum depends on the damage distribution in each block, the temperature and the material.

VII. CONCLUSIONS

Cumulative damage procedures based on a local stress-strain approach which includes an adequate description of metal processing, plastic deformation history and resulting residual stresses, can adequately predict fatigue for uniaxial stress at temperatures where metal deformation is time dependent. The extension of these procedures to biaxial stressing and elevated temperatures is possible for limited cases but much remains to be done before general applicability is possible. Models for reversed plastic deformation capable of describing structural plasticity have been successfully applied to several metals and geometries. Load history characterization by generalized models is on the other hand applicable only in a few restricted cases.

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